

# X-ray Evidence for Supermassive Black Holes in Non-Active Galaxies:

## Detection of X-ray Flare Events, Interpreted as Tidal Disruptions of Stars by SMBHs

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**Abstract.** It has long been suggested that supermassive black holes in non-active galaxies might be tracked down by occasional tidal disruptions of stars on nearly radial orbits. A tidal disruption event would reveal itself by a luminous flare of electromagnetic radiation. Theorists argued that the convincing detection of such a tidal disruption event would be the observation of an event which fulfills the following three criteria: (1) the event should be of finite duration (a ‘flare’), (2) it should be very luminous (up to  $L_{\max} \approx 10^{45}$  erg/s in maximum), and (3) it should reside in a galaxy that is otherwise perfectly *non-active* (to be sure to exclude an upward fluctuation in gaseous accretion rate of an *active* galaxy). During the last few years, several X-ray flare events were detected which match exactly the above criteria. We therefore consider these events to be excellent candidates for the occurrences of the theoretically predicted tidal disruption flares. In this contribution, we review the previous observations of giant X-ray flares from normal galaxies, present new results on these objects, critically discuss alternatives to the favored outburst scenario, and report results from our ongoing search for further tidal disruption flares based on the *ROSAT* all-sky survey database.

## 1 Flares from tidally disrupted stars as probes for the presence of SMBHs in *non-active* galaxies

There is strong evidence for the presence of massive dark objects at the centers of many galaxies. Does this hold for *all* galaxies? Questions of particular interest in the context of AGN evolution are: what fraction of galaxies have passed through an active phase, and how many now have non-accreting and hence unseen supermassive black holes (SMBHs) at their centers (e.g., Lynden-Bell 1969, Rees 1988)? Several approaches were followed to study these questions. A lot of effort has concentrated on the determination of central object masses from studies of the *dynamics of stars and gas* in the nuclei of nearby galaxies. Earlier (ground-based) evidence for central quiescent dark masses in non-active galaxies has been strengthened by recent HST results (see Kormendy & Richstone 1995 for a review).

Whereas the dynamics of stars and gas probe rather large volumes, i.e., distances from the SMBH, high-energy *X-ray emission* originates from the very vicinity of the SMBH (see Komossa 2001 for a review). In *active* galaxies, excellent evidence for the presence of SMBHs is provided by the detection of luminous

hard power-law like X-ray emission, rapid variability, and the detection of relativistically broadened FeK $\alpha$  lines (e.g., Tanaka et al. 1995). How can we find *dormant* SMBHs in *non-active* galaxies? Lidskii & Ozernoi (1979) and Rees (1988) suggested to use the flare of electromagnetic radiation produced when a star is tidally disrupted and accreted as a means to detect SMBHs in nearby non-active galaxies.

A star on a radial ‘loss-cone’ orbit gets tidally disrupted after passing a certain distance to the black hole (e.g., Hills 1975, Lidskii & Ozernoi 1979, Diener et al. 1997), the tidal radius, given by

$$r_t \simeq 7 \cdot 10^{12} \left( \frac{M_{\text{BH}}}{10^6 M_\odot} \right)^{\frac{1}{3}} \left( \frac{M_*}{M_\odot} \right)^{-\frac{1}{3}} \frac{r_*}{r_\odot} \text{ cm} . \quad (1)$$

The star is first heavily distorted, then disrupted. About 50%–90% of the gaseous debris becomes unbound and is lost from the system (e.g., Young et al. 1977, Ayal et al. 2000). The rest will eventually be accreted by the black hole (e.g., Cannizzo et al. 1990, Loeb & Ulmer 1997). The stellar material, first spread over a number of orbits, quickly circularizes (e.g., Rees 1988, Cannizzo et al. 1990) due to the action of strong shocks when the most tightly bound matter interacts with other parts of the stream (e.g., Kim et al. 1999). Most orbital periods will then be within a few times the period of the most tightly bound matter (e.g., Evans & Kochanek 1989). A star will only be disrupted as long as its tidal radius lies outside the Schwarzschild radius of the BH, else it is swallowed as a whole (this happens for BH masses larger than  $\sim 10^8 M_\odot$ ).<sup>1</sup> More massive BHs may still disrupt or strip the atmospheres of giant stars.

## 2 Tidal disruption flares from non-active galaxies: observational evidence

### 2.1 Summary of X-ray and optical observations

With the X-ray satellite *ROSAT*, some rather unusual observations have been made in the last few years: the detections of giant-amplitude, non-recurrent X-ray outbursts from a handful of *optically non-active* galaxies, starting with the

<sup>1</sup> Numerical simulations of the disruption process, the stream-stream collision, the accretion phase, and the depletion of loss-cone orbits and disruption rates have been studied in the literature (e.g., Nolthenius & Katz 1983, Carter & Luminet 1985, Evans & Kochanek 1989, Laguna et al. 1993, Diener et al. 1997, Ayal et al. 2000, Kim et al. 1999, Hills et al. 1975, Kato & Hoshi 1978, Gurzadyan & Ozernoi 1980, Cannizzo et al. 1990, Loeb & Ulmer 1997, DiStefano et al. 2001, Frank & Rees 1976, Magorrian & Tremaine 1999; see Komossa & Dahlem 2001 for more references, incl. a few observations of *active* galaxies that might be related to tidal disruption events). Renzini et al. (1995; R95) reported the detection of a UV flare from the (only mildly active) galaxy NGC 4552. The luminosity was several orders of magnitude weaker than what could have been expected from a tidal disruption event. Tidal stripping of a star’s atmosphere is one possible explanation (R95).

**Table 1.** Summary of the X-ray properties of the flaring non-active galaxies during outburst (NGC 5905: Bade et al. 1996, Komossa & Bade 1999, RXJ1242–1119: Komossa & Greiner 1999, RXJ1624+7554: Grupe et al. 1999, RXJ1420+5334: Greiner et al. 2000; for first results on another candidate see Reiprich & Greiner 2001. Based on the position they report, we refer to this source as RXJ1331–3243).  $T_{\text{bb}}$  denotes the black body temperature derived from a black body fit to the data (cold absorption was fixed to the Galactic value in the direction of the individual galaxies).  $L_{\text{x,bb}}$  gives the intrinsic luminosity in the (0.1–2.4) keV band, based on a black body fit. We note that this is a lower limit to the actual peak luminosity, since we most likely have not caught the sources exactly at maximum light, since the spectrum may extend into the EUV, and since we have conservatively assumed no X-ray absorption intrinsic to the galaxies.

galaxy name	redshift $z$	$kT_{\text{bb}}$ [keV]	$L_{\text{x,bb}}$ [erg/s]
NGC 5905	0.011	0.06	$3 \cdot 10^{42*}$
RXJ1242–1119	0.050	0.06	$9 \cdot 10^{43}$
RXJ1624+7554	0.064	0.097	$\sim 10^{44}$
RXJ1420+5334	0.147	0.04	$8 \cdot 10^{43}$
RXJ1331–3243	0.051		

\* Mean luminosity during the outburst; since the flux varied by a factor  $\sim 3$  during the observation, the peak luminosity is higher.

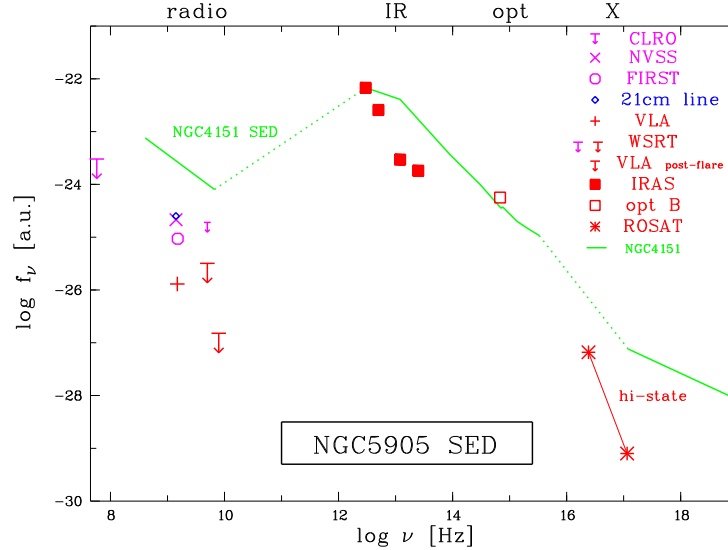
case of NGC 5905 (Bade et al. 1996, Komossa & Bade 1999). Based on the huge observed outburst luminosity, the observations were interpreted in terms of tidal disruption events. Below, we first give a brief review of the properties of all published X-ray flaring non-active galaxies, and then present results from a search for radio emission from these galaxies. There are now four X-ray flaring ‘normal’ galaxies (NGC 5905, RXJ1242–1119, RXJ1624+7554, RXJ1420+ 5334<sup>2</sup>), and a possible fifth candidate (RXJ1331–3243), all of which show similar properties (see Table 1 for a summary):

- huge X-ray peak luminosity (up to  $\sim 10^{44}$  erg/s),
- giant amplitude of variability (up to a factor  $\sim 200$ ),
- ultra-soft X-ray spectrum ( $kT_{\text{bb}} \simeq 0.04\text{--}0.1$  keV),
- absence of optical signs of Seyfert activity (the spectrum of NGC 5905 is of HII-type; the other galaxies do not show any emission lines).

## 2.2 Radio observations

Radio observations are important for two reasons: Firstly, they allow the search for a peculiar, optically hidden AGN at the center of each flaring galaxy. Secondly, radio emission could possibly be produced in relation to the X-ray flare

<sup>2</sup> The X-ray position error circle of RXJ1420+53 contains a second galaxy for which a spectrum is not yet available. Based on the galaxy’s morphology, Greiner et al (2000) argue that it is likely non-active



**Fig. 1.** Multiwavelength continuum spectrum of NGC 5905 (symbols represent data from Israel & Mahoney 1990, van Moorsel 1982, Condon et al. 1998, Becker et al. 1995, Hummel et al. 1987, Brosch & Krumm 1984, Komossa & Dahlem 2001, NED, Bade et al. 1996, Komossa & Bade 1999; the solid/dotted line corresponds to the continuum of the galaxy NGC 4151, shown for comparison). Note: data were taken with different aperture sizes and resolution, and at different times.

itself. We have performed a search for radio emission from the X-ray flaring galaxies, based on the NRAO VLA Sky Survey (NVSS) catalogue (Condon et al. 1998) at 1.4 GHz, and the FIRST VLA sky survey at 1.5 GHz (e.g., Becker et al. 1995). With the exception of NGC 5905, no flaring galaxy is radio-detected. For NGC 5905, several radio observations from the literature are available, summarized in Fig. 1. The bulk of the radio emission is extended, and NGC 5905 does not show any peculiar radio properties as compared to other similar spiral galaxies. Dedicated VLA radio observations of the nucleus of NGC 5905, performed at a frequency of 8.46 GHz several years after the X-ray outburst, provided an upper limit of 0.15 mJy for the presence of a central point source (Komossa & Dahlem 2001).

### 3 Outburst scenarios

Most outburst scenarios do not survive scrutiny (Komossa & Bade 1999), because they cannot account for the huge maximum luminosity (e.g., X-ray binaries within the galaxies, or a supernova in a dense environment), are inconsistent with the optical observations (gravitational lensing), or predict a different temporal behavior (X-ray afterglow of a Gamma-ray burst; see, e.g., Fig. 2 of Bradt et

al. 2001). A critical discussion of AGN-related scenarios (presence of a dusty warm absorber, or other absorption-related variability), and why they are highly unlikely, is given by Komossa & Dahlem (2001).

### 3.1 Tidal disruption model

Except for some types of GRB-related emission mechanisms, the huge peak outburst luminosity nearly inevitably calls for the presence of a SMBH. This, in combination with the complete absence of any signs of AGN activity, makes tidal disruption of a star by a SMBH the most plausible outburst mechanism.

Intense electromagnetic radiation will be emitted in three phases of the disruption and accretion process: First, during the stream-stream collision when different parts of the bound stellar debris interact with themselves (e.g., Rees 1988, Kim et al. 1999). Secondly, radiation is emitted during the accretion of the stellar material. Finally, the unbound stellar gas leaving the system may shock the surrounding interstellar matter and cause intense emission, like in a supernova remnant (Khokhlov & Melia 1996).

Although many details of the actual tidal disruption process are still unclear, some basic predictions have been repeatedly made in the literature how a tidal disruption event should reveal itself observationally: (1) the event should be of finite duration (a ‘flare’), (2) it should be very luminous (up to  $L_{\max} \approx 10^{45}$  erg/s in maximum), and (3) it should reside in a galaxy that is otherwise perfectly *non*-active (to be sure to exclude an upward fluctuation in gaseous accretion rate of an *active* galaxy). All three predictions are fulfilled by the X-ray flaring galaxies; particularly by NGC 5905 and RXJ1242–1119, which are the two best-studied cases so far.

In addition, we can do some further order of magnitude estimates and consistency checks. The luminosity emitted if the black hole is accreting at its Eddington luminosity can be estimated by

$$L_{\text{edd}} \simeq 1.3 \times 10^{38} M/M_{\odot} \text{ erg/s.} \quad (2)$$

In case of NGC 5905, a BH mass of at least a few  $\sim 10^4 M_{\odot}$  would be required to produce the observed luminosity, and a higher mass if  $L_{\text{x}}$  was not observed at its peak value. For comparison, a BH mass of NGC 5905 of  $M_{\text{BH}} \approx 10^7 M_{\odot}$  would be inferred, based on the correlation between bulge blue luminosity and BH mass for spiral galaxies (Salucci et al. 2000), or even up to a few  $10^8 M_{\odot}$  if we use the correlation reported mostly for ellipticals by Ferrarese & Merritt (2001; their ‘sample A’, their Fig. 1). For the other galaxies, using again  $L_{\text{edd}}$ , we infer BH masses reaching up to a few  $10^6 M_{\odot}$ . Alternative to a complete disruption event, the atmosphere of a giant star could have been stripped. It is also interesting to note that NGC 5905 possesses a complex bar structure (Friedli et al. 1996) which might aid in the fueling process by disturbing the stellar velocity fields.

In a simple black body approximation, the temperature of the accretion disk scales with black hole mass as

$$T \simeq 8 \cdot 10^4 \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)^{\frac{1}{12}} \text{ K (at } r_{\text{t}}), \quad T \simeq 2 \cdot 10^7 \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)^{-\frac{1}{4}} \text{ K (at } 3 r_{\text{S}}). \quad (3)$$

This gives  $T_{\text{tidal}} \simeq 3 \cdot 10^5 \text{ K}$ ,  $T_{3r_s} \simeq 7 \cdot 10^5 \text{ K}$  for  $M=10^6 M_\odot$ , where  $r_s$  is the Schwarzschild radius. Using black body fits of the X-ray flare spectra we find temperatures in a similar range;  $T_{\text{obs}} \simeq (4\text{--}10) \cdot 10^5 \text{ K}$ . Like in AGN, X-ray powerlaw tails are possible. They might have escaped detection during the observations, since weak, or they may develop only after a certain time after the start of the accretion phase. We soon expect first results from a *Chandra* and *XMM* observation of RXJ1242–1119, which will give valuable constraints on the post-flare evolution.

The Eddington time scale for the accretion of the stellar material is given by

$$t_{\text{edd}} \simeq 4 \eta_{0.1} (M_{\text{BH}}/10^6 M_\odot) (M_*/0.1 M_\odot) \text{ yrs}. \quad (4)$$

Uncertainties in estimating the total duration of the tidal disruption event arise from questions like: how much material is actually accreted or expelled, does a strong wind develop, etc. The events are expected to last for months to years (e.g., Rees 1988). Observationally, the duration of the events was at least several days, followed by gaps in the observations. The source fluxes were then significantly down several years later (e.g., Fig. 9 of Komossa & Bade 1999).

Finally, we note that the redshift distribution of the few sources observed so far is consistent with the predicted tidal disruption rate, in the sense that the events are sufficiently distant to define a large volume of space, in which the detection of a few events would be expected.

### 3.2 Search for further X-ray flares

We performed a search for further X-ray flaring activity using the sample of nearby galaxies of Ho et al. (1995) and *ROSAT* all-sky survey (Voges et al. 1999) and archived pointed observations. 136 out of the 486 galaxies in the catalogue were observed at least twice with *ROSAT*. We do not find another flaring normal galaxy in this sample, entirely consistent with the expected tidal disruption rate of one event in at least  $\sim 10^4$  years per galaxy (e.g., Magorrian & Tremaine 1999).

## 4 Outlook

X-ray outbursts from non-active galaxies provide important information on the presence of SMBHs in these galaxies, and the link between active and normal galaxies. Future X-ray surveys, like those planned with the *LOBSTER* ISS X-ray all-sky monitor, *ROSITA* and *MAXI*, will be valuable in finding more of these outstanding sources. Rapid follow-up observations at all wavelengths will then be important. In particular, X-ray observations with high spectral and temporal resolution might open up a chance to probe the realm of strong gravity, since the temporal evolution of the stellar debris will depend on relativistic precession effects around the Kerr metric.

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